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DISCOVERY OF OPTICAL BURSTS FROM MS 1603.6+2600 = UW CRB

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ABSTRACT

We report the discovery of several optical burst-like events from the low-mass X-ray binary MS 1603.6+2600 (UW CrB). The events last for a few tens of seconds, exhibit a very fast rise and slow decay, and involve optical brightening of a factor of 2–3. The flares appear distinct from the lower level flickering and instead strongly resemble reprocessed type-I X-ray bursts as seen in a number of other neutron star low-mass X-ray binaries. In conjunction with the previously reported candidate X-ray burst, these confirm that the compact object in UW CrB is a neutron star. We examine the optical burst brightness and recurrence times and discuss how the nature of the system can be constrained. We conclude that the source is most likely an accretion disk corona source at an intermediate distance, rather than a nearby quiescent system or very distant dipper.

Subject headings: accretion, accretion disks — binaries: close — binaries: eclipsing — stars: individual: UW CrB — X-rays: binaries — X-rays: bursts —

1. INTRODUCTION

The X-ray source MS 1603.6+2600 was discovered in the Einstein Extended Medium Sensitivity Survey (Gioia et al. 1990) and associated with a faint ($R = 19.4$) optical counterpart designated UW CrB (Morris et al. 1990). Its nature has remained a puzzle. Morris et al. (1990) found the counterpart to be an eclipsing binary with an orbital period of 111.04 min and considered the source to be either a cataclysmic variable or low-mass X-ray binary (LMXB) hosting a neutron star. The emission line spectrum and optical to X-ray flux ratio favored the LMXB interpretation, with an accretion disk corona (ADC) source most likely. The implied distance was large, 30–80 kpc, making this high latitude source a halo object. Hakala et al. (1998) reconsidered these possibilities and proposed another alternative – a quiescent low-mass X-ray binary, likely a black hole system, which is much closer to us. An important clue was subsequently provided by Mukai et al. (2001) who identified a strong X-ray flare in *ASCA* data. While this appeared to resemble a type-I X-ray burst, the authors did not consider this identification conclusive. If the event was a type-I burst then it was faint, indicating either a very distant object in the halo, or an ADC source. Based on the X-ray lightcurve, Mukai et al. (2001) favored the former of these interpretations, arguing that the source is a dipper rather than an ADC source. Finally, Jonker et al. (2003) reported new *Chandra* observations of the source, and favored the ADC interpretation, although they allowed that a quiescent system was still possible if the earlier X-ray flare was not a type-I burst. They rejected the distant dipper scenario, arguing that the optical luminosity would then be too high for a compact 2 hr binary.

From a more theoretical standpoint, Ergma & Vilhu (1993) considered several evolutionary scenarios for the LMXB case, including degenerate and non-degenerate hydrogen rich mass donors and evolved helium stars. Again, bursts could be a crucial diagnostic. The presence, recurrence time, and duration of bursts can discriminate between systems with different mass transfer rates (e.g., the degenerate and non-degenerate cases discussed by Ergma & Vilhu 1993), and the burst properties will be sensitive to the chemical composition of the accreted material.

To date, the only published X-ray burst from this source was that reported by Mukai et al. (2001), and this only yielded 60 counts. It is possible to also search for bursts in the optical, as the optical counterpart, while faint, is accessible to rapid photometry. Type-I X-ray bursts are expected to be manifested in the optical via reprocessed X-ray emission. This behavior has been widely seen in many other LMXBs for several decades (e.g., Grindlay et al. 1978 and many subsequent works). Optical bursts are dramatic, involving a brightening of a factor ~ 2. Ultraviolet bursts are also present and are even more dramatic (Hynes et al. 2004).

We report here rapid optical photometry of UW CrB. The primary goal of the program was to resolve the flickering contamination of the orbital variability, and this study will be presented separately. However, several optical bursts were serendipitously discovered, and we discuss those here.

2. OBSERVATIONS

UW CrB was observed over several nights from 2004 April 16–26 using the Argos fast CCD camera (Nather & Mukadam 2004) on the McDonald Observatory 2.1 m telescope. A total of 25 hrs of good data were obtained; details are provided in Table 1. Observations were obtained with a broadband BVR filter (Rolyn Optics No. 66.2475, bandpass $\sim 4000-7500$ Å) to maximize count rates and hence allow exposure times of 5 or 10 s. The data were taken as a continuous sequence of images with negligible intervening dead-time. Conditions were mostly near-photometric with 1–2 arcsec seeing and no Moon. The nights of April 18, 20, and 26 experienced poorer transparency and/or seeing.

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Table 1
Log of observations

Date (2004)	UT Range	Good time (ks)[a]	Exposure time (s)	Bursts
April 16	08:04:21–11:43:11	11.4	10	1
April 18	10:14:53–11:29:03	4.1	10	0
April 20	06:28:40–11:25:55	5.8[b]	10	0
April 21	08:01:05–11:37:65	13.0	10	1
April 22	07:39:13–11:26:33	13.6	5	1
April 23	05:43:09–11:31:19	20.9	5	1
April 25	09:20:34–11:40:34	8.0	5	0
April 26	05:35:11–06:58:11	4.8	5	0
	06:58:26–10:45:36	9.0[b]	10	0

[a]Total period when reliable differential photometry could be obtained, not always uninterrupted.
[b]These long runs occurred in very poor conditions and limited interrupted good intervals occurred; some bursts may have been missed.

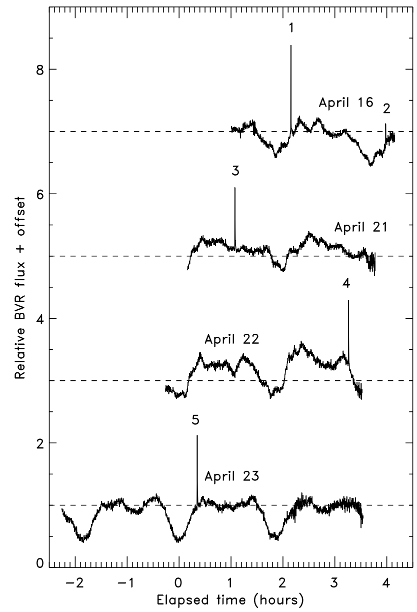

Fig. 1.— Selected lightcurves of UW CrB. Only those exhibiting bursts are shown. All lightcurves have been normalized relative to the mean flux level observed during the run. Offsets have been applied to avoid overlap; dashed lines indicate the unit flux level for each curve. Lightcurves have been shifted by an integral number of orbital periods to bring eclipses into alignment, but no attempt has been made to absolutely phase them. 5 s lightcurves have been rebinned to 10 s resolution for clarity and consistency. Numbers indicate bursts.

Data reduction employed a combination of iraf routines to generate calibration files and then a custom IDL pipeline to apply calibrations and extract photometry. Bias structure and dark current were subtracted using many dark exposures of the same duration as the object frames. Residual time-dependent bias variations were removed using two partial bad columns which are not light sensitive. Sensitivity variations were removed using flatfield exposures of the inside of the dome; we verified that this flattened the average sky background and hence that no illumination correction was necessary.

Photometry was extracted using standard aperture photometry techniques. For each lightcurve, the aperture was chosen to minimize the scatter between stars C and V of Hakala et al. (1998), and differential photometry of UW CrB was then performed relative to star C. Adopted apertures were typically 1.0–1.5 arcsec in radius.

3. LIGHTCURVES

We show the lightcurves containing bursts in Fig. 1. These exhibit a typical range of morphologies for this source (Hakala et al. 1998), with eclipses sometimes being very deep, and sometimes barely detectable. Superposed on the orbital modulations and low-level flickering are several very sharp, large amplitude burst-like events, involving a flux increase of a factor of 2–3. We will discuss their origin in Section 4, but here we will anticipate the conclusion by characterizing them in the same terms commonly used for type-I X-ray bursts.

The events appear to be real, being resolved in time and exhibiting no anomalies in the point spread function (PSF). Event 2 is of lower brightness than the others, but also appears resolved in time and has a normal PSF.

To characterize the bursts we fit a simple model consisting of an instantaneous rise and exponential decay. As the burst peak is unresolved in the data, we rebin this model to match the data in fitting. Free parameters are the burst amplitude, start-time, and e-folding decay time. Expanded views of each burst are shown in Fig. 2 together with the best fitting models. Results are summarized in Table 2, based on fitting data from −20 s to +60 s. We quote the relative fluence, expressed as individual burst fluence values divided by the mean fluence of bursts 1, 3, 4, and 5, and the burst durations τ, defined by van Paradijs, Penninx, & Lewin (1988) as the burst fluence divided by the peak flux. The latter is obviously crudely constrained as the peaks are not actually resolved. For both quantities we quote both values from the model fit and those derived directly from the data. The relative fluences derived are similar with both methods. The durations differ significantly, however. Durations derived from the data probably overestimate the burst duration, as the burst peak is unresolved and hence the peak flux will be underestimated. In contrast, the model assumes a sharper peak than is seen in type-I bursts, so will underestimate the duration compared to such bursts. Hence the two values obtained for each burst should bracket its true duration. Given that we do not resolve the peak, this is probably the best estimate that can be made.

The bursts are, with the exception of the weak event 2, very uniform in properties. The burst fluence is constant to within 10 %, and burst durations (including event 2) are all consistent with a value of 5–15 s if measured from the model (probably an underestimate), or 15–30 s from the unresolved data (an overestimate). "True" values of the burst duration (in the sense of van Paradijs, Penninx, & Lewin 1988) are likely to be in the 10–20 s range for these bursts (for example, events 4 and 5 which are better resolved).

Burst recurrence times can be crudely estimated from the data, although are subject to small number statistics and sampling problems. We observed four full bursts in

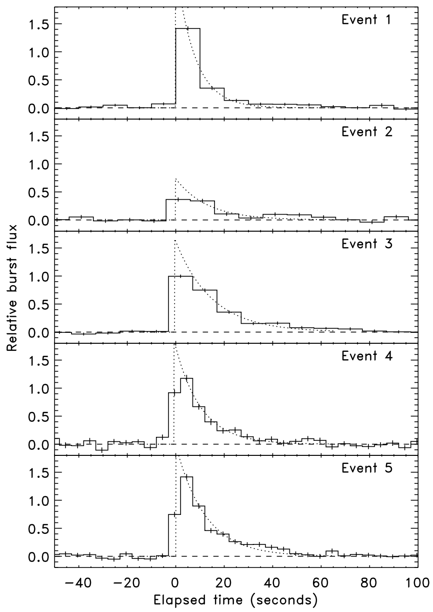

FIG. 2.— Expanded view of each candidate type-I burst. Histograms indicate the data with statistical error-bars. The dotted line is an exponential decay fit to each burst. As in Fig. 1, fluxes are relative to the source mean brightness and so can be directly compared. The persistent level has been subtracted off using fluxes immediately before and after each burst.

TABLE 2
PROPERTIES OF BURST FITS

Burst	Relative fluence[a]		Duration (s)	
	Model	Observed	Model[b]	Observed
1	0.91	0.93	7.8	15.2
2	0.43	0.45	13.6	28.9
3	1.11	1.09	15.0	25.3
4	0.90	0.92	10.7	18.2
5	1.08	1.06	12.1	17.2

[a]Relative to the mean of bursts 2, 4, 5, and 6.
[b]For the exponential decay model, the duration is equal to the e-folding time.

90.6 ks (25.2 hrs) of good data, or an average of 1 per 6.3 hrs. If the bursts occur randomly (i.e., as Poisson distributed events) then recurrence times of between 3.8 and 11 hrs have a 10 % or greater chance of producing 4 events in this period (i.e., longer or shorter recurrence times would be excluded at 90 % confidence). Of course, if the events are type-I X-ray bursts then they are not distributed as Poisson events but occur quasi-regularly. In that case, the statistics could be biased by our once-per-day sampling. More robust constraints are that the longest period continuously observed without a burst being seen is 3.5 hrs, and the shortest period between *observed* bursts is 21.1 hrs. Both arguments suggest that an average recurrence time of much less than 4 hrs is very unlikely. Recurrence times of up to $\sim$ 12 hrs are possible, or around 24 hrs if they were synchronized with our observations, and irregular enough to allow intervals as short as 21.1 hrs.

4. DISCUSSION

4.1. *Comparison with type-I bursts*

It has already been suggested by Mukai et al. (2001) that a type-I X-ray burst was seen by *ASCA*. The optical events that we see also exhibit characteristics typical of type-I bursts. The implied duration of $\tau \sim 10 - 20$ s, the fast rise and slow decay, and optical brightening of a factor $\sim 2 - 3$ are all similar to reprocessed optical bursts seen in other objects (e.g., Grindlay et al. 1978; Schoembs & Zoeschinger 1990; Robinson & Young 1997; Homer, Charles, & O'Donoghue 1998; and other works). The burst frequency, one per $\sim$ 4.2 hrs, is also normal.

Event 2 breaks the pattern of otherwise uniform burst fluences, but has a similar duration to the other events. It is also the only burst seen in the same lightcurve as another, suggesting that it could be a mini-burst produced when the first burst (event 1) leaves unspent fuel on the neutron star surface. Such behavior is seen in other LMXBs (e.g., Gottwald et al. 1986).

The uniformity of fluences also presents suggestive, if not conclusive, evidence for the location of reprocessing of the bursts. Since UW CrB is a high inclination system, if the burst reprocessing were dominated by the inner face of the companion star, we would expect large changes in the brightness of optical bursts dependent on orbital phase. In particular, event 3 occurs near phase 0.5 when the inner face of the companion is viewed nearly face-on, hence should be stronger than the other bursts which all appear to occur in eclipse ingress or egress. This is not seen, indicating that the burst reprocessing is probably dominated by the disk.

4.2. *Optical flares in quiescent systems*

Hakala et al. (1998) suggested that UW CrB might be a quiescent LMXB, possibly harboring a black hole. In this case an alternative flaring mechanism is needed. Quiescent LMXBs containing both black holes and neutron stars do undergo relatively rapid optical flaring (e.g., Zurita, Casares, & Shahbaz 2003; Hynes et al. 2003), and this behavior was already considered by Jonker et al. (2003) as a possible explanation for the X-ray flare of Mukai et al. (2001). Indeed, the black hole candidate XTE J1650–500 has exhibited *non-thermal* X-ray flares otherwise very similar to type-I bursts in a low state (Tomsick, Kalemci, Corbel, & Kaaret 2003). In the case of A 0620–00 at least, the optical events can be relatively rapid, occurring on timescales comparable to those seen here (Hynes et al. 2003). While the observed amplitudes are much smaller, that is probably a consequence of dilution of the accretion light by the companion star, and the undiluted disk light could undergo variations of a factor of two or more. In spite of these similarities, the lightcurves shown in Fig. 1 appear completely different to those of quiescent LMXBs. The burst-like events we see are single discrete events, and do not appear to belong to the general range of flickering behavior. The similarity of burst fluences is also rather unlike the kind of stochastic events seen in quiescent LMXBs to date. We therefore consider this explanation of the bursts to be very unlikely, and that the type-I burst interpretation is far more plausible.

4.3. *The nature of UW CrB*

Now that we have seen both an X-ray burst-like event (Mukai et al. 2001), and multiple optical events, it is hard to escape the conclusion that UW CrB is an X-ray burster. This immediately rules out white dwarf and black hole models for the system; the compact object is a neutron star. The burst properties and recurrence time further constrain the accretion rate. The short burst recurrence time rules out a quiescent system. Such systems can exhibit type-I bursts, but the recurrence time is estimated to be 10–60 yrs, or even more (Cornelisse et al. 2002), a direct consequence of the very low accretion rate onto the neutron star.

The probable 4–12 hr recurrence time and 10–20 s burst duration are both typical of intermediate luminosity bursting LMXBs (van Paradijs, Penninx, & Lewin 1988; Strohmayer & Bildsten 2003) and suggest that UW CrB is not accreting at an unusually low rate; hence its low X-ray brightness must indicate either extreme distance or an ADC source as discussed in Section 1. In contrast, for example, Aql X-1 was observed to exhibit optical bursts lasting over a minute and recurring once per hour (Robinson & Young 1997). Both short recurrence times and long bursts are believed to be often associated with low accretion rates (Strohmayer & Bildsten 2003), yet are not seen in UW CrB.

It is also of value to compare our observations with those of GS 1826–24 (Homer, Charles, & O'Donoghue 1998). Both GS 1826–24 and UW CrB are neutron star LMXBs having orbital periods ~ 2 hr; thus the sizes of the two systems should be very similar. If we assume that the intrinsic optical burst luminosity is simply a function of the X-ray burst strength and reprocessing disk area (and hence orbital period), then we might expect similar luminosity reprocessed bursts in the two systems, assuming that X-ray bursts have comparable peak luminosities, and similar disk geometries. GS 1826–24 is a low-inclination system, however, whereas UW CrB is eclipsing and hence high inclination. In a high inclination system we see less projected disk area, so if reprocessing is dominated by the disk (as suggested by the lack of phase dependence in the optical burst fluences), then we would expect to observe weaker optical bursts at a given distance. This is not the case, however; both UW CrB and GS 1826–24 are of comparable optical brightness and exhibit optical bursts rising to a peak $\sim 2\times$ the persistent optical level, indicating that the observed optical burst flux is actually comparable in the two systems. This would imply, subject to the assumptions made, that UW CrB is somewhat closer than GS 1826–24, or at least not much further away. The distance to GS 1826–24 is estimated at less than 7.5 ± 0.5 kpc by Kong et al. (2000), so unless bursts in UW CrB are substantially more luminous than in GS 1826–24, or reprocessing into optical emission is much more efficient, we would expect a comparably nearby distance for UW CrB. This contradicts the extreme distances inferred for the dipper scenario (e.g., 75 kpc Mukai et al. 2001) and instead favors the ADC model. Note that this argument is essentially similar to that made by Jonker et al. (2003), but complements it as we have used the optical burst brightness rather than the persistent level. The argument is approximate and model dependent, but is sufficient to indicate that UW CrB should not be $10\times$ further away than GS 1826–24 as has been previously suggested.

5. CONCLUSIONS

We have reported the discovery of several resolved optical bursts from UW CrB. These are almost certainly reprocessed type-I X-ray bursts, clarifying several characteristics of the source. i) For type-I bursts, the compact object must be a neutron star rather than a black hole or white dwarf. ii) The burst rate is relatively high, indicating an active rather than quiescent system, and thus a distance greater than a few kpc. iii) The optical burst flux is comparable to the similar source GS 1826–24, suggesting a comparable distance ($\lesssim 10$ kpc). It is thus most likely that UW CrB is an ADC source (as also argued by Jonker et al. 2003) rather than a distant dipper. Given its high Galactic latitude and intermediate distance, however, it must still be situated in the Galactic halo.

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REFERENCES

Cornelisse, R., Verbunt, F., in't Zand, J. J. M., Kuulkers, E., & Heise, J. 2002, A&A, 392, 931
Ergma, E., Vilhu, O. 1993, A&A, 277, 483
Gioia, I. M., Maccacaro, T., Schild, R. E., Wolter, A., Stocke, J. T., Morris, S. L., & Henry, J. P. 1990, ApJS, 72, 567
Gottwald, M., Haberl, F., Parmar, A. N., & White, N. E. 1986, ApJ, 308, 213
Grindlay, J. E., McClintock, J. E., Canizares, C. R., Cominsky, L., Li, F. K., Lewin, W. H. G., & van Paradijs, J. 1978, Nature, 274, 567
Hakala, P. J., Chaytor, D. H., Vilhu, O., Piirola, V., Morris, S. L., & Muhli, P. 1998, A&A, 333, 540
Homer, L., Charles, P. A., & O'Donoghue, D. 1998, MNRAS, 298, 497
Hynes, R. I., Charles, P. A., Casares, J., Haswell, C. A., Zurita, C., & Shahbaz, T. 2003, MNRAS, 340, 447
Hynes, R. I., et al., in preparation
Jonker, P. G., van der Klis, M., Kouveliotou, C., Méndez, M., Lewin, W. H. G., & Belloni, T. 2003, MNRAS, 346, 684
Kong, A. K. H., Homer, L., Kuulkers, E., Charles, P. A., & Smale, A. P. 2000, MNRAS, 311, 405
Morris, S. L., Liebert, J., Stocke, J. T., Gioia, I. M., Schild, R. E., & Wolter, A. 1990, ApJ, 365, 686
Mukai, K., Smale, A. P., Stahle, C. K., Schlegel, E. M., & Wijnands, R. 2001, ApJ, 561, 938
Nather, R. E. & Mukadam, A. S. 2004, ApJ, 605, 846
Robinson, E. L. & Young, P. 1997, ApJ, 491, L89
Schoembs, R. & Zoeschinger, G. 1990, A&A, 227, 105
Strohmayer, T., Bildsten, L. 2003, to appear in Compact Stellar X-Ray Sources, eds. W. H. G. Lewin and M. van der Klis, Cambridge University Press
Tomsick, J. A., Kalemci, E., Corbel, S., & Kaaret, P. 2003, ApJ, 592, 1100
van Paradijs, J., Penninx, W., & Lewin, W. H. G. 1988, MNRAS, 233, 437

Zurita, C., Casares, J., & Shahbaz, T. 2003, ApJ, 582, 369